PREPARED FOR THE U.S. DEPARTMENT OF ENERGY,
UNDER CONTRACT DE-AC02-76-CHO-3073

PPPL-2811
UC-427

PPPL-2811

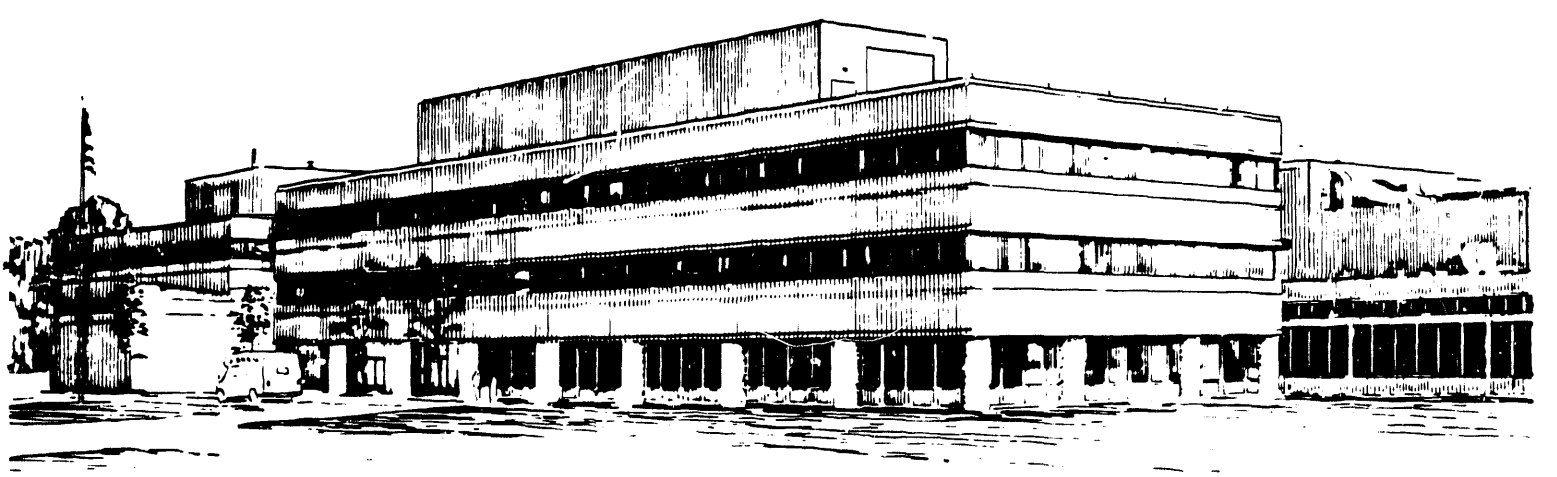
FLOW SHEAR SUPPRESSION OF TURBULENCE USING EXTERNALLY DRIVEN ION BERNSTEIN AND ALFVÉN WAVES

BY

H. BIGLARI, M. ONO, P.H. DIAMOND, AND G.G. CRADDOCK

January 1992

PRINCETON PLASMA PHYSICS LABORATORY



PRINCETON UNIVERSITY, PRINCETON, NEW JERSEY

NOTICE

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial produce, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

NOTICE

This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from the:

Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831;
Prices available from (615) 576-8401.

Available to the public from the:

National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161
703-487-4650

PPPL--2811

DE92 006644

FLOW SHEAR SUPPRESSION OF TURBULENCE USING EXTERNALLY DRIVEN ION BERNSTEIN AND ALFVÉN WAVES

H. Biglari,† M. Ono,† P. H. Diamond,* and G. G. Craddock‡

†*Plasma Physics Laboratory, Princeton University, Princeton, NJ 08543*
**Department of Physics, University of California at San Diego, La Jolla, CA 92093*
‡*Science Applications International Corporation, San Diego, CA 92121*

Abstract

The utilization of externally-launched radio-frequency waves as a means of active confinement control through the generation of sheared poloidal flows is explored. For low-frequency waves, kinetic Alfvén waves are proposed, and are shown to drive sheared $\mathbf{E} \times \mathbf{B}$ flows as a result of the radial variation in the electromagnetic Reynolds stress. In the high frequency regime, ion Bernstein waves are considered, and shown to generate sheared poloidal rotation through the ponderomotive force. In either case, it is shown that modest amounts of absorbed power ($\sim$ few 100 kW) are required to suppress turbulence in a region of several cm radial width.

MASTER

I. INTRODUCTION

The suppression of edge turbulence by sheared plasma flows (and consequently, the radial electric fields associated with them) has emerged as the leading paradigm to explain the improvement of confinement in the transition from L- to H-mode.[1] The basic idea is that in the presence of rotational $\mathbf{E} \times \mathbf{B}$ shear, fluctuations experience enhanced decorrelation and are shorn apart before they have had time to grow to large amplitudes. The criterion for turbulence suppression is roughly given by

$$\left|\frac{d\langle v_\theta \rangle}{dr}\right| > C_0 \frac{\Delta\omega_{k'}}{k'_\theta \Delta x_{k'}}, \tag{1}$$

where $\langle v_\theta \rangle = -c\langle E_r \rangle / B_0$ is the $\mathbf{E}\times\mathbf{B}$ flow, k'_θ, $\Delta\omega_{k'}$, and $\Delta x_{k'}$ are the poloidal wavenumber, decorrelation frequency, and radial correlation length of the ambient turbulence, respectively, and $C_0 \lesssim 1$ is a model-dependent parameter that accounts for how much the general criterion $\langle v_\theta \rangle' > (\Delta\omega_{k'}/k'_\theta \Delta x_{k'})$ overestimates the velocity shear needed for turbulence suppression. As the sign of the shear is irrelevant to this argument, it is possible to effect a transition to an improved state of confinement with either sign of the electric field, a prediction of the theory that has been experimentally corroborated.[2] Indeed, observations of locally reduced turbulence in the vicinity of shear layers even in non-H-mode discharges[3] suggest that this mechanism is robust and of general applicability. One is therefore naturally led to inquire whether it is possible to *actively* control plasma confinement quality through the generation of sheared flows by *external, non-intrusive* means (thus, for example, dodging the inherent limitations associated with electrode insertion[2]). Given the wall-sputtering disadvantages associated with neutral beam injection,[4] the utilization of externally-launched radio-frequency waves in this capacity lends itself as an intriguing possibility which we consider in this work. For low-frequency waves, we propose kinetic Alfvén waves (KAW), which are shown to drive sheared $\mathbf{E} \times \mathbf{B}$ flows as a result of the radial variation in the electromagnetic Reynolds stress.[5] In the high frequency regime, we consider ion Bernstein waves (IBW), and show that they generate sheared poloidal rotation through the ponderomotive force. In either case, it is shown that modest amounts of absorbed power ($\sim$ few 100 kW) are required to suppress turbulence in a region of several cm radial width.

II. KINETIC ALFVÉN WAVE FLOW DRIVE

We first consider the application of kinetic Alfvén waves in connection with sheared flow drive and turbulence suppression at the plasma edge.[5] To minimize losses due to radial attenuation, the location of the Alfvén resonance r_A [where $\omega = k_{\|}(r_A)v_A$] is taken to be very close to the plasma edge. The time evolution of the average poloidal flow, in the low-frequency, cylindrical approximation, is driven by the electromagnetic Reynolds flux and damped by neoclassical magnetic pumping:

$$\frac{\partial\langle v_\theta\rangle}{\partial t} = \frac{d\langle\mathcal{S}\rangle}{dr} - \mu_{neo}\langle v_\theta\rangle, \tag{2}$$

where $\langle\mathcal{S}\rangle = v_A^2\,\langle\tilde{B}_r\tilde{B}_\theta/B_0^2\rangle - \langle\tilde{v}_r\tilde{v}_\theta\rangle$ is the electromagnetic Reynolds stress (or equivalently, ponderomotive pressure), $\mu_{neo} = \alpha\nu_{ii}$ is the magnetic pumping frequency ($\alpha \simeq \epsilon = r/R$ in the plateau regime and $\sim \omega_{ti}^2/\nu_{ii}^2$ in the Pfirsch-Schlüter regime), and $(\tilde{\mathbf{v}}, \tilde{\mathbf{B}})$ are the KAW velocity and magnetic field fluctuations. Equation (2) indicates that for rotational flow to be generated, one must have *i)* radially propagating waves (since for standing waves, the cross-correlations are identically zero), and *ii)* an imbalance between the fluid and magnetic stresses. These criteria are satisfied by KAW's, for which the radial wave vector is complex, and ion inertia introduces an imbalance between electric and magnetic fluctuations. Thus, $k_r = k_r^R + ik_r^I$, where $k_r^R\rho_s = [(\omega^2/k_{\|}^2v_A^2) - 1]^{1/2}$ characterizes the radially propagating component of the wave vector ($\rho_s = c_s/\Omega_i$, $c_s^2 = 2T_e/m_i$ is the sound speed, and $\Omega_i = eB_0/m_ic$), and $k_r^I/k_r^R = \delta_e/2$ characterizes the evanescence scale length, where δ_e is electron dissipation. For a collisionless ($\omega_{te} \gg \nu_e$) plasma, $\delta_e = \pi(\omega/|\omega_{te}|)\exp(-\omega^2/\omega_{te}^2)$, and for a collisional ($\omega_{te} \ll \nu_e$) plasma, $\delta_e = \omega\omega_{te}^2/\nu_e\,[\omega^2 + (\omega_{te}^2/\nu_e)^2]$, where $\omega_{te} = k_{\|}v_{te}$. Using $\tilde{A}_{\|k} = (1 + k_\perp^2\rho_s^2)\,(k_{\|}c/\omega)\,\tilde{\phi}_k$ as appropriate for KAW's, we obtain $\langle\mathcal{S}\rangle = k_r^Rk_\theta\rho_s^2\,k_\perp^2\rho_s^2\,c_s^2\,\langle|e\tilde{\phi}/T_e|^2\rangle$, and for steady flows,

$$\frac{\langle v_\theta\rangle}{c_s} = \delta_e\,\frac{\omega^2}{\mu_{neo}k_\theta c_s}\left\langle\left|\frac{\tilde{\xi}_r(r_A)}{\rho_s}\right|^2\right\rangle\left(\frac{\omega^2}{k_{\|}^2v_A^2} - 1\right)^2\exp(-2k_r^I|r - r_A|), \tag{3}$$

where $\tilde{\xi}_r = d\tilde{v}_r/dt$ is the radial displacement vector. Substituting this expression into Eq. (1), we obtain the amount of absorbed power required to

suppress turbulence over a radial width Δr:

$$P_{abs} > \frac{\pi^2}{2} m_i n_i \, aR \, \rho_s \, c_s^2 \, \delta_e^{-2} \frac{C_0 \Delta\omega_{k'}}{k'_\theta \Delta x_{k'}} \frac{\omega \mu_{neo}}{\Omega_i k_\theta c_s} \frac{\rho_s}{L_n} \left(\frac{\omega^2}{k_\parallel^2 v_A^2} - 1 \right)^{-5/2} \exp(2k_i^R \Delta r), \tag{4}$$

where $L_n^{-1} = -d \ln n_i / dr$ is the density scale length, and a and R are the plasma minor and major radius, respectively. In deriving Eq. (4), $\tilde{\xi}_r$ was eliminated in terms of the absorbed power to which it is related by[6] $P_{abs} = (\pi/4) \, aR\omega \, (|\tilde{\xi}_r|^2 / k_\theta^2) \times d(4\pi m_i n_i \omega^2 - k_\parallel^2 B_0^2)/dr$. As an example, assuming drift wave-like turbulence ($\Delta\omega_{k'} \sim \omega_{*e} = k_\theta c T_e / eBL_n$, $k'_\theta \Delta x_{k'} \sim 1$, and $k'_\theta \rho_s \sim 0.2$), for TEXT edge parameters ($B_0 = 20$ kG, $n_0 = 5 \times 10^{12}$ cm^{-3}, $T_e = 30$ eV), $P_{abs} = 300$ kW is required for a 3 cm wide zone of enhanced confinement. Similar estimates for the edge of DIII-D ($B_0 = 21$ kG, $n_0 = 10^{13}$ cm^{-3}, and $T_e = 150$ eV) indicate that $P_{abs} = 300$ kW will result in a 4 cm wide turbulence suppression zone.

III. PONDEROMOTIVE FLOW GENERATION BY ION BERNSTEIN WAVES

One of the dilemmas of thermonuclear fusion research is that confinement quality in the plasma core must be simultaneously high enough to allow for the possibility of ignition, yet low enough so as to allow for the rapid removal of helium ash. An *active* knob with which confinement quality in the plasma core could be regulated would therefore be a major boon to the fusion program. It is with this motivation in mind that we now turn to the possibility of using high-frequency RF waves to suppress *core* plasma turbulence through the generation of sheared rotation. The proposed RF scheme must *i)* be able to access the high-temperature plasma interior, *ii)* have very short perpendicular wavelength (as shall become clear momentarily), *iii)* have high power density, and *iv)* not adversely affect plasma confinement in other ways. As a working paradigm, we consider here the utilization of ion Bernstein waves in this regard. These quasi-electrostatic waves, for which $n_\perp^2 \gtrsim K_{zz} \gg n_\parallel^2 \sim K_{xx} \sim K_{xy}$, and $\tilde{E}_x \gg \tilde{E}_z \gg \tilde{E}_y$, satisfy the dispersion relation

$$\frac{n_\perp^2}{K_{zz}} + \frac{n_\parallel^2}{K_{xx}} \simeq 1, \tag{5}$$

where $\mathbf{n} = c\mathbf{k}/\omega$, $\mathbf{k} = k_\perp \hat{\mathbf{e}}_x + k_\parallel \hat{\mathbf{e}}_z$, and K_{xx}, K_{xy}, and K_{zz} are the elements of the hot plasma dielectric tensor[7] and incorporate cyclotron damping on the minority species (in K_{xx}) and electron Landau damping (in K_{zz}). The total power absorbed comes predominantly from the sloshing energy of the ions and given by $P_{abs}/A \simeq (v_{ph\perp}/4\pi)\,|\tilde{E}_x|^2\,\partial K_{xx}/\partial \ln b_i$, where $v_{ph\perp} = \omega/k_\perp$, and $b_i = k_\perp^2 \rho_i^2/2$. The perpendicular ion flow pattern associated with the wave is

$$\begin{pmatrix} \tilde{v}_x \\ \tilde{v}_y \end{pmatrix}_i \simeq i\,\frac{\omega\Omega_i}{\omega_{pi}^2} \begin{pmatrix} K_{xx} \\ K_{xy,i} \end{pmatrix} \frac{c\tilde{E}_x}{B_0}, \tag{6}$$

where the subscript 'i' refers to ions. The nonlinearly-generated, ponderomotive ion poloidal flow at steady state is then given by

$$\langle v_y \rangle \simeq \mu_{neo}^{-1} \langle \tilde{\mathbf{v}} \cdot \nabla \tilde{\mathbf{v}}_y \rangle \simeq \left(\frac{\omega\Omega_i}{\omega_{pi}^2}\right)^2 \frac{k_\perp^R}{\mu_{neo}}\, K_{xx}\, |K_{xy,i}| \left\langle \left| \frac{c\tilde{E}_x(r_0)}{B_0} \right|^2 \right\rangle \exp(-2k_\perp^I |x - r_0|). \tag{7}$$

where $(k_\perp^R, k_\perp^I)$ represent the radially propagating and evanescent components of the perpendicular wavenumber, and r_0 is the radial location of the resonance layer. Eliminating the field amplitude in terms of the absorbed power and substituting into Eq. (1), we obtain the power requirement to suppress turbulence over a layer of radial width Δr:

$$P_{abs} > \frac{r_0 R B^2}{4}\, \frac{c^2 v_{ti}^2}{v_A^4}\, \frac{\mu_{neo}}{\omega}\, \frac{C_0 \Delta\omega_{k'}}{k'_\theta \Delta x_{k'}}\, \frac{n_\perp^2 - K_{zz}}{n_\parallel^2 K_{zz}}\, \frac{\partial \ln K_{xx}/\partial b_i}{|K_{xy,i}|}\, \frac{\exp(2k_\perp^I \Delta r)}{k_\perp^I}. \tag{8}$$

A simple estimate of the (cyclotron) damping decrement $k_\perp^I$ can be obtained from the field fall-off, i.e., $(k_\perp^I R)^{-1} \sim \Delta B/B \sim (\omega - \Omega_{i,m})/\omega \sim 3k_\parallel v_{ti,m}/\omega$, where the subscript '$m$' denotes the minority ion species. Again, assuming drift wave-like turbulence for the case of PLT ($B_0 = 30$ kG, $n_0 = 3\cdot 10^{13}$ cm^{-3}, $T_i = 1$ keV, $R = 132$ cm, $r_0 = 40$ cm), we find $P_{abs} > 300$ kW for confinement enhancement over a 7cm wide radial zone. It is interesting to note that there have been a number of experiments which have observed confinement improvement, turbulence suppression, and/or poloidal rotation generation in connection with IBW heating. On PLT,[8] for example, the energy confinement time with the application of 650 kW IBWH yielded a factor 1.7 improvement over the value associated with neutral beam-heated L-mode discharges at the same density. Furthermore, the electrostatic density fluctuations, as measured by microwave scattering, were observed to drop in magnitude by

a significant factor relative to the *equivalent-density* ohmic phase, while the frequency spectrum was Doppler-shifted, suggesting a net increase of the poloidal rotation velocity. Further evidence of confinement improvement with the application of IBWH comes from JIPPTII-U,[9] where transport analysis shows that the ion thermal diffusivity, χ_i, decreases with the application of 400 kW of IBW in the vicinity of the core plasma region where the wave is deposited. The reduction in transport coefficients is accompanied by a sharp steepening of the density profiles.

In summary, our calculations indicate that RF waves afford a promising means of actively controlling plasma confinement quality. We have found that modest amounts ($\sim$ several hundred kW) of power are required to cause a local suppression of turbulence and consequent confinement improvement either at the plasma edge or in the plasma core. The possibility of helicity injection current drive has also been explored and will be presented elsewhere.

ACKNOWLEDGMENTS

This work was supported by the U. S. Department of Energy Contracts #DE-AC02-76-CHO3073 and #DE-FG03-85-ER53275.

REFERENCES

[1]H. Biglari, P. H. Diamond, P. Terry, *Phys. Fluids B* **2**, 1 (1990); H. Biglari, P. H. Diamond, *et al.*, in *Plasma Physics and Controlled Fusion Research 1990* (IAEA, Vienna, 1991) in press.

[2]R. Weynants *et al.*, in *Plasma Physics and Controlled Fusion Research 1990, ibid.*; A. Boileau, *et al.*, submitted to *Nucl. Fusion*; R. J. Taylor, private communication.

[3]Ch. P. Ritz *et al.*, *Phys. Rev. Lett.* **63**, 2543 (1990).

[4]T. Ohkawa and R. L. Miller, in *Plasma Physics and Controlled Fusion Research 1990, ibid.*; A. Hassam, submitted to *Phys. Rev. Lett.*

[5]G. G. Craddock and P. H. Diamond, submitted to *Phys. Rev. Lett.*

[6]A. Hasegawa and L. Chen, *Phys. Fluids* **17**, 1399 (1974).

[7]T. H. Stix, *Theory of Plasma Waves* (McGraw-Hill, New York, 1962).

[8]M. Ono, *et al.*, *Phys. Rev. Lett.* **60**, 294 (1988).

[9]T. Seki *et al.*, *Proc. of the Ninth Topical Conf. on Radio Frequency Power in Plasmas*, Charleston, SC, August 19-21, 1991.

EXTERNAL DISTRIBUTION IN ADDITION TO UC-420

Dr. F. Paoloni, Univ. of Wollongong, AUSTRALIA
Prof. M.H. Brennan, Univ. of Sydney, AUSTRALIA
Plasma Research Lab., Australian Nat. Univ., AUSTRALIA
Prof. I.R. Jones, Flinders Univ, AUSTRALIA
Prof. F. Cap, Inst. for Theoretical Physics, AUSTRIA
Prof. M. Heindler, Institut für Theoretische Physik, AUSTRIA
Prof. M. Goossens, Astronomisch Instituut, BELGIUM
Ecole Royale Militaire, Lab. de Phy. Plasmas, BELGIUM
Commission-European, DG. XII-Fusion Prog., BELGIUM
Prof. R. Boucique, Rijksuniversiteit Gent, BELGIUM
Dr. P.H. Sakanaka, Instituto Fisica, BRAZIL
Instituto Nacional De Pesquisas Espaciais-INPE, BRAZIL
Documents Office, Atomic Energy of Canada Ltd., CANADA
Dr. M.P. Bachynski, MPB Technologies, Inc., CANADA
Dr. H.M. Skarsgard, Univ. of Saskatchewan, CANADA
Prof. J. Teichmann, Univ. of Montreal, CANADA
Prof. S.R. Sreenivasan, Univ. of Calgary, CANADA
Prof. T.W. Johnston, INRS-Energie, CANADA
Dr. R. Bolton, Centre canadien de fusion magnétique, CANADA
Dr. C.R. James,, Univ. of Alberta, CANADA
Dr. P. Lukác, Komenského Universzita, CZECHO-SLOVAKIA
The Librarian, Culham Laboratory, ENGLAND
Library, R61, Rutherford Appleton Laboratory, ENGLAND
Mrs. S.A. Hutchinson, JET Library, ENGLAND
Dr. S.C. Sharma, Univ. of South Pacific, FIJI ISLANDS
P. Mähönen, Univ. of Helsinki, FINLAND
Prof. M.N. Bussac, Ecole Polytechnique,, FRANCE
C. Mouttet, Lab. de Physique des Milieux Ionisés, FRANCE
J. Radet, CEN/CADARACHE - Bat 506, FRANCE
Prof. E. Economou, Univ. of Crete, GREECE
Ms. C. Rinni, Univ. of Ioannina, GREECE
Dr. T. Mual, Academy Bibliographic Ser., HONG KONG
Preprint Library, Hungarian Academy of Sci., HUNGARY
Dr. B. DasGupta, Saha Inst. of Nuclear Physics, INDIA
Dr. P. Kaw, Inst. for Plasma Research, INDIA
Dr. P. Rosenau, Israel Inst. of Technology, ISRAEL
Librarian, International Center for Theo Physics, ITALY
Miss C. De Palo, Associazione EURATOM-ENEA , ITALY
Dr. G. Grosso, Istituto di Fisica del Plasma, ITALY
Prof. G. Rostangni, Istituto Gas Ionizzati Del Cnr, ITALY
Dr. H. Yamato, Toshiba Res & Devel Center, JAPAN
Prof. I. Kawakami, Hiroshima Univ., JAPAN
Prof. K. Nishikawa, Hiroshima Univ., JAPAN
Director, Japan Atomic Energy Research Inst., JAPAN
Prof. S. Itoh, Kyushu Univ., JAPAN
Research Info. Ctr., National Instit. for Fusion Science, JAPAN
Prof. S. Tanaka, Kyoto Univ., JAPAN
Library, Kyoto Univ., JAPAN
Prof. N. Inoue, Univ. of Tokyo, JAPAN
Secretary, Plasma Section, Electrotechnical Lab., JAPAN
S. Mori, Technical Advisor, JAERI, JAPAN
Dr. O. Mitarai, Kumamoto Inst. of Technology, JAPAN
J. Hyeon-Sook, Korea Atomic Energy Research Inst., KOREA
D.I. Choi, The Korea Adv. Inst. of Sci. & Tech., KOREA
Prof. B.S. Liley, Univ. of Waikato, NEW ZEALAND
Inst of Physics, Chinese Acad Sci PEOPLE'S REP. OF CHINA
Library, Inst. of Plasma Physics, PEOPLE'S REP. OF CHINA
Tsinghua Univ. Library, PEOPLE'S REPUBLIC OF CHINA
Z. Li, S.W. Inst Physics, PEOPLE'S REPUBLIC OF CHINA
Prof. J.A.C. Cabral, Instituto Superior Tecnico, PORTUGAL
Dr. O. Petrus, AL I CUZA Univ., ROMANIA
Dr. J. de Villiers, Fusion Studies, AEC, S. AFRICA
Prof. M.A. Hellberg, Univ. of Natal, S. AFRICA
Prof. D.E. Kim, Pohang Inst. of Sci. & Tech., SO. KOREA
Prof. C.I.E.M.A.T, Fusion Division Library, SPAIN
Dr. L. Stenflo, Univ. of UMEA, SWEDEN
Library, Royal Inst. of Technology, SWEDEN
Prof. H. Wilhelmson, Chalmers Univ. of Tech., SWEDEN
Centre Phys. Des Plasmas, Ecole Polytech. SWITZERLAND
Bibliotheek, Inst. Voor Plasma-Fysica, THE NETHERLANDS
Asst. Prof. Dr. S. Cakir, Middle East Tech. Univ., TURKEY
Dr. V.A. Glukhikh,Sci. Res. Inst. Electrophys.I Apparatus, USSR
Dr. D.D. Ryutov, Siberian Branch of Academy of Sci., USSR
Dr. G.A. Eliseev, I.V. Kurchatov Inst., USSR
Librarian, The Ukr.SSR Academy of Sciences, USSR
Dr. L.M. Kovrizhnykh, Inst. of General Physics, USSR
Kernforschungsanlage GmbH, Zentralbibliothek, W. GERMANY
Bibliothek, Inst. Für Plasmaforschung, W. GERMANY
Prof. K. Schindler, Ruhr-Universität Bochum, W. GERMANY
Dr. F. Wagner, (ASDEX), Max-Planck-Institut, W. GERMANY
Librarian, Max-Planck-Institut, W. GERMANY
Prof. R.K. Janev, Inst. of Physics, YUGOSLAVIA

DATE
FILMED
314192

I